SAND75-0451
Unlimited Release
Printed March 1976

MAGMA ENERGY RESEARCH PROJECT

Project Summary
July 1, 1974 - June 30, 1975

John L. Colp, 5710A
Mark J. Davis, 5830
Edward J. Graeber, 5825
Harry C. Hardee, 1543

Sandia Laboratories
Albuquerque, NM 87115

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $5.00; Microfiche $2.25

CONTENTS

	Page
Introduction	7
Summary of Previous Efforts	7
Magma Source Location and Identification Study	9
Magma Properties and Material Compatibility Studies	11
Source Tapping Studies	12
Energy Extraction Studies	12
Scientific and Technical Activities	12
A. General	12
B. Source Location and Definition	15
Discussion	15
Achievements	17
Future Plans	17
C. Source Tapping	17
Achievements	18
Future Plans	19
D. Magma Characterization	19
Discussion	19
Achievements	21
Future Plans	21
E. Magma Materials Compatibilities	22
Discussion	22
Achievements	23
Future Plans	24
F. Energy Extraction Studies	24
Discussion	24
Achievements	31
Future Plans	33
General Activities	34
A. Publications	34
B. Presentations	34
C. Conferences Attended	35
D. Meetings and Consultations	35
E. Requests for Information	36

MAGMA ENERGY RESEARCH PROJECT

INTRODUCTION

The objective of the Magma Energy Research Project now under way at Sandia Laboratories is to investigate the feasibility of extracting energy directly from deeply buried circulating magma sources. With temperatures of the order of 1000°C, these buried sources represent great amounts of high-quality energy. Project plans describe a concept whereby a fully closed heat exchanger system is inserted directly into such a magma source to allow the heat energy to be brought to the surface with minimal environmental impact. The conversion of this heat energy to a usable form, such as electricity, at the surface could utilize reasonably conventional techniques (Figure 1). To determine whether such plans are potentially possible to achieve, whether they are technically feasible to achieve, and whether they are economical if achieved, are the long-range targets of the project.

The program is organized in such a way that, if at any time in its progress it becomes apparent that a real physical law precludes the possibility of successful completion, the regret costs of the entire program can be minimized. Because this project is recognized to be long-term in nature, it is not being directed toward any nearby deadline for power production. Steps in the program are being taken cautiously until the initial obstacles have been shown to be surmountable.

SUMMARY OF PREVIOUS EFFORTS

The initial proposal by Sandia Laboratories to investigate the extraction of thermal energy from buried molten rock deposits was put forward in mid-1973. From that proposal, investigatory studies on a small scale were commenced. That level of effort was continued until mid-1974 when the initial funding for the project (at that time called Magma Tap) was received from ERDA (then AEC) Division of Physical Research.

During that initial year it became apparent that a logical approach would be to divide the project into four phases. This division would permit the application of an interdisciplinary, across-the-laboratory application of specialized talents and facilities. The coordination of these diverse efforts and their application toward the solution of the overall problem was made through the work of a Project Engineer. The following summarizes the work accomplished in each of these phases during the initial year's effort.

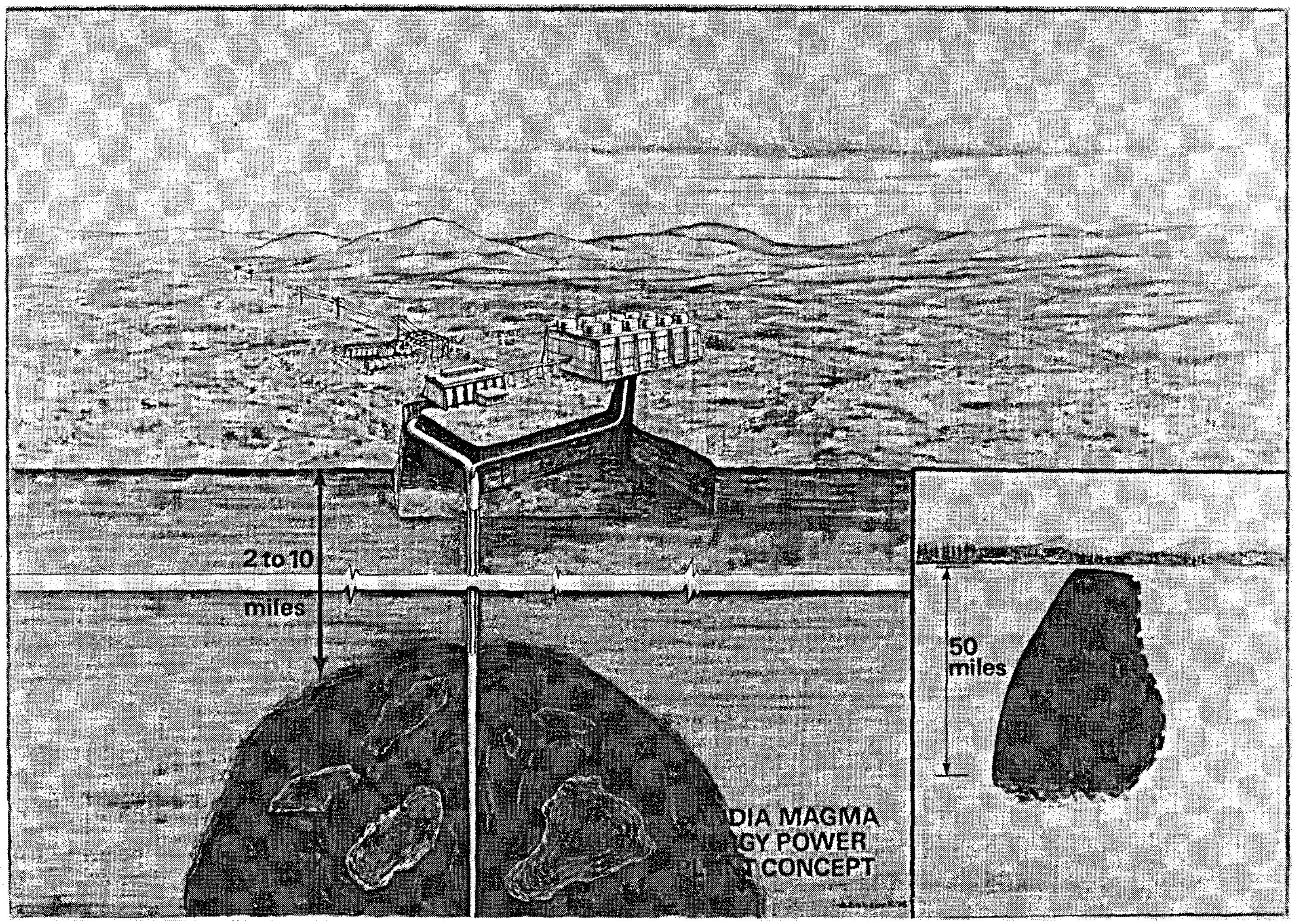

Figure 1

Magma Source Location and Identification Study

a. As part of the initial effort, a study was begun to evaluate possible methods for locating and identifying magma sources. A survey of the literature published on the subject revealed that, although there had been much previous work done in the field of subsurface instrumental sensing, very little had been directed toward looking for molten rock. Only one instance of the possible recognition of a molten region was found in the Western literature. However, a few references to Russian work toward this objective were noted.

Concurrent with the literature survey, several visits and discussions with groups of investigators and users of subsurface sensing methods were made. Visits were made to the USGS offices at Denver and Menlo Park, Colorado School of Mines; University of California at Riverside, Texas A&M University; the University of Texas; University of Hawaii at Manoa; and the NASA Johnson Space Center. From these visits it became apparent that Sandia was one of few groups considering the possibility of locating and identifying magma sources for geothermal purposes. It also became apparent that at that time, no appreciable effort had been expended on the problem of instrumentally locating and identifying a magma source in the conterminous United States.

b. The University of Hawaii was working on a geothermal program to tap the thermal energy of the hot brine expected to be below the island of Hawaii. One method of exploring the subsurface for the brine pockets was by electrical dipole resistivity measurements, which was also a technique which had been suggested to search for magma sources on the mainland. Therefore, Sandia was interested in the success of the survey techniques applied in Hawaii. A major problem with the dipole method was the difficulty in implanting electrodes in the lava with sufficiently low contact resistance. As a cooperative effort with the University, Sandia offered to implant the electrodes, using air-dropped earth penetrators as the electrode. During the week of December 2, 1973, a total of 29 terradynamic electrodes were implanted. It appeared that good electrical contact (100 to 200 ohms) was achieved in all sites other than about six in relatively new lava with no soil cover or vegetation. The electrical contact using penetrators appeared to be better than that for electrodes implanted by other methods. A reason for using the air-dropped penetrators was the inaccessibility to many of the target areas by heavy equipment.

c. A preliminary survey was performed of possible locations of magma sources in western United States. The guidelines used for selecting the locations were simple: (1) knowledge of a volcanic eruption in historic times, (2) knowledge of a volcanic material flow less than 10,000 years ago, and (3) surface evidence of a very great thermal anomaly in the subsurface. The 36 locations selected with the aid of USGS personnel are not all the possible magma locations in these areas and, certainly, the inclusion of a location should not be taken as an indication that the location is being considered for future magma exploration (see Figure 2).

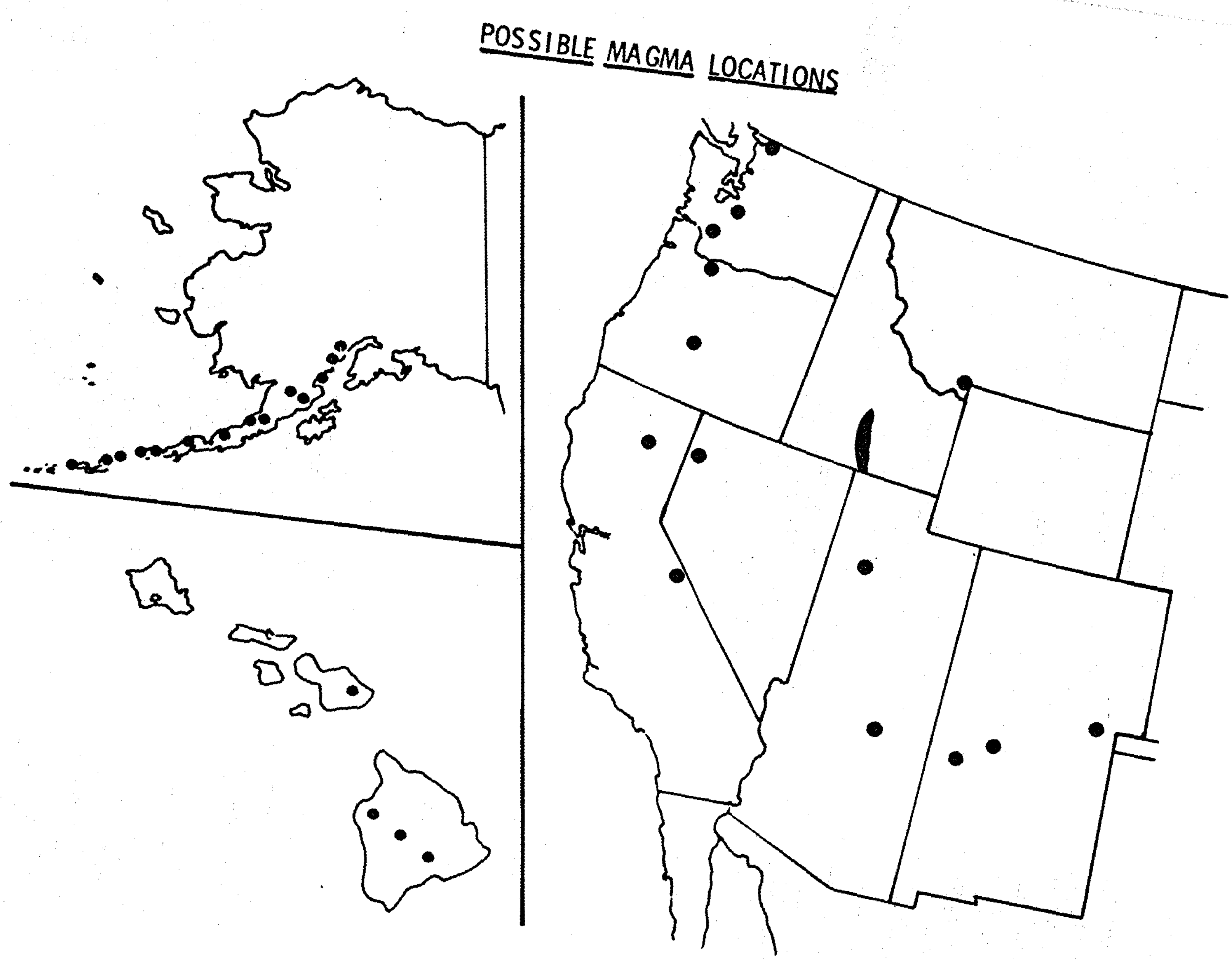

Figure 2

Magma Properties and Material Compatibility Studies

Rock analyses were conducted for characterization to support materials compatibility studies which utilize the molten rock as a laboratory simulant for magma. Two oceanic basalts were acquired as test rocks: (1) fresh pillow basalt and flow fragments dredged from a peak on the East Pacific Rise (EPR) (provided by Dr. R. Fisher, Scripps Institution), and (2) pahoehoe Hawaiian Tholeiitic (HT) basalt, surface picked from the September 1971 Kilauea fissure flow. Results from analyses as related to the analytical method employed in characterizing these rocks are summarized below.

1. Thermogravimetric and mass spectrometric analyses showed that EPR loses 0.3 weight percent as compared with 0.08 weight percent for HT; both lost 90 percent of their total weight loss below 600°C. The noncondensable gases evolved were primarily H_2O with minor CO and CO_2. For the EPR basalt, H_2S was also released and, above 600°C, SO_2, SO, and COS became important species.

2. Gamma ray spectroscopy disclosed the presence of ^{40}K, ^{137}Cs, ^{138}La, and ^{226}Ra, which were expected, since K, La, and U occur in significant abundance in the earth's crust.

3. Petrographic and X-ray diffraction analyses indicate that both basalts were essentially glass with some phenocrysts of pyroxene, plagioclase, and olivine. Magnetite was present in both. EPR might be characterized as an alkali basalt, whereas HT is a tholeiite.

4. Chemical analyses obtained by wet methods, atomic absorption, and electron microprobe also characterized the rock types as alkali and tholeiitic; ferrous iron in HT was reduced from 10.50 to 6.66 percent FeO by heating to 1200°C for 19 hours.

These analyses indicate the complete characterization of the test rocks and also show that subsequent material corrosion tests should be conducted in closed, pressurized vessels so that contact between gases and engineering test materials can be sustained.

Another aspect of the measurement of the magma properties was the suggested use of an instrumented penetrometer to measure the properties of in-situ magma in an active volcano flow, before the lava is exposed to air or cools. Two penetrometers were designed and built to measure deceleration (3 channels of data) and temperature (2 radiometers and 2 thermocouples). Each penetrometer weighed 200 pounds, was to be air dropped into a volcanic flow, and was parachute-retarded to control the impact velocity and trajectory angle. The intent was to drop the magma penetrometers during the test program for implanting the terradynamic electrodes, but no volcanoes were active during that time period and the penetrometers were returned to Sandia to await another test opportunity.

Source Tapping Studies

No work was begun on this facet.

Energy Extraction Studies

Preliminary, long-term, heat extraction rates were calculated for assumed magma fields. These rates ranged from 1 to 20 kw/ft^2 of tube area depending on the assumptions used. Preliminary model experiments were started for a long recirculating tube heat exchanger design which could eventually be used in an actual magma field.

A turbine generator unit was assembled and tested in the laboratory, and a long-tube boiler heat exchanger was designed and ordered for a model heat exchanger experiment. Facilities were available at Sandia to melt and maintain in a molten state 100 pounds of magma. One or more series of tests in this facility were planned. The primary purpose of the tests is to study such a phenomenon as the temperature gradient across the magma and into the heat exchanger. Secondarily, the experiment will serve as a laboratory demonstration of the conversion of the heat of molten rock into electricity.

SCIENTIFIC AND TECHNICAL ACTIVITIES

A. GENERAL

Two activities conducted over this reporting period were of a general nature applicable to all phases of the project. They were the establishment of the Magma Energy Advisory Panel and the planning and holding of the Sandia/USGS Magma Workshop.

1. In undertaking a project of the diversity encountered in magma energy research, it is unlikely that any single installation will possess the wide-range expertise that is required. Nor is it probably desirable to obtain all of the required diverse talents on a full-time basis at project outset. These facts were recognized, and the Magma Energy Advisory Panel was formed early in this reporting year. It consists of persons from institutions throughout the United States carefully selected for their recognized expertise in particular relevant fields.

The members of the Panel for this year, their affiliations, and their fields of expertise are:

Prof. Robert Decker, Dartmouth College, Volcanology/Geophysics
Dr. Dallas Peck, USGS National Center, Magma Petrology
Prof. Melvin Friedman, Texas A&M University, Tectonophysics/Rock Deformation
Dr. Peter Ward, USGS Menlo Park, Geophysics/Seismic Studies
Prof. John Hermance, Brown University, Geophysics/Electrical
Prof. Roger Staehle, Ohio State University, Material Compatibility
Prof. William Brigham, Stanford University, Heat Transfer/Source

The panel's purpose is to review the progress of the project and to provide advice on directions in which it should proceed. Each member is to provide advice and assistance in his specialty to those persons at Sandia responsible for that part of the project.

The panel meets as a body on a semiannual basis. Individual consultations between panel members and principal investigators occur on a frequent basis as the need arises.

2. The Sandia/USGS Magma Workshop was convened to address two objectives:

> To assess the present state of knowledge of the occurrence of magma bodies, the chemical and physical properties of in-situ magma, and the methods of exploration for magma.
>
> To recommend the most critically needed research and development in these areas.

Following two preliminary planning sessions (October 1974 and December 1974), The Magma Workshop met March 3-6, 1975. The participants invited were specially selected for their backgrounds and recognized competence in the magma-related fields of corrosion engineering, geochemistry, geology, geophysics, heat flow, heat transfer physics, igneous petrology, metallurgy, mineralogy, seismology, tectonophysics, and volcanology.

The stipulated format for the operation of the Workshop was that there would be no recordings of the discussions, there would be no formal published proceedings, and each participant would have the opportunity to review the draft of the published assessments and recommendations prior to final publication. This format was adopted to encourage free and complete discussions on the part of each participant. The Sandia report, SAND75-0306, is the only published record of the Magma Workshop.

In preparation for the Workshop, an annotated bibliography on the subjects of: (1) physical properties of magma, (2) distribution and configuration of magma bodies, and (3) prospecting for magma bodies was prepared at Dartmouth College under the direction of Professor Robert W. Decker. Draft copies were provided to each Workshop participant prior to the meeting. The formal, revised volume of this bibliography is being published as an unlimited distribution Sandia Laboratories' document, SAND75-0307.

The program of the Magma Workshop consisted of two full days of discussions with all participants, meetings of three individual working groups, and a final summary session of working-group presentations with all participants.

The three working groups were as follows:

1. Structural Geology of Magma Bodies
   Prof. Robert W. Decker, Leader

2. Chemical and Physical Properties of Magma
   Dr. Dallas L. Peck, Leader

3. Search For and Evaluation of Magma Chambers
   Dr. Peter L. Ward, Leader

Magma bodies were discussed from the different points of view of the three working groups.

1. The structural geology of magma bodies focused on the analogy that cooled plutons, exposed by erosion to various depths below the land surface that existed at the time of their emplacement, give good insight into the depth, size, shape, and internal nature of potential magma bodies that may exist in the subsurface today.

2. Chemical and physical properties of magma was the concern of the largest group at the meeting. Knowledge of these properties is essential for evaluating the feasibility of extracting energy directly from magma bodies. Finding a magma body, drilling and emplacing a heat-transfer device into magma, and extracting energy from magma all require thorough knowledge of various physical and chemical properties of naturally occurring molten rock. Thirteen of twenty-six properties of magma considered by this group were ranked as poorly known.

3. The search for and evaluation of magma chambers by geophysical techniques was the final point of view. Since no magma chamber has been located definitely anywhere in the world, no one knows for certain what exploration methods are most useful. However, the inferred contrast in physical properties between magma and country rock suggests that several geophysical techniques may be able to identify magma bodies whose size are more than half their depth of burial. The need for better knowledge of the physical properties of magma was reinforced by this group.

Recommendations from the Workshop covered a wide range of concerns, but all groups emphasized the need to select a site in the western conterminous U. S. of a potential shallow magma body and to begin intensive field studies, geophysical surveys, and test drill holes with the ultimate goal of emplacing an experimental energy extraction device into the molten rock. Prior to or simultaneously with this experimental field effort, geologists should re-examine cooled magma bodies exposed by erosion for better clues to the nature of the internal processes during crystallization. Did and does a magma body convect is a key question to the entire magma energy extraction concept. Determination of the poorly known physical and chemical properties of subsurface magma, either recreated in the laboratory or measured in situ, is another major recommendation. Evaluation of geophysical exploration techniques on a "known" or reasonably certain magma body such as Kilauea Iki lava lake in Hawaii might reasonably precede field surveys at the test site. And finally, computer modeling of a dynamic magma body should prove useful in determining which parameters are most critical for a practical if not complete knowledge of a hypothetical magma body from which energy may be tapped.

The complete reports of the assessments and recommendations prepared by each of the working groups are found in SAND 75-0306.

B. SOURCE LOCATION AND DEFINITION (J. L. Colp, Principal Investigator)

Discussion

Critically important to the Project is developing the ability to locate and identify a source of molten rock in the subsurface. It is imperative that the existence of a magma source, its depth, its areal extent, and its general form (whether in a finite pool or in a honeycomb of crevices filled with molten material) be known with the greatest degree of certainty before proceeding with plans for drilling. Discussions at the aforementioned Magma Workshop indicated that little is known at this time about the precise location and the physical configuration of magma sources. What knowledge exists is based almost entirely on intuitive evidence from areas near active volcanos and eroded structures of ancient volcanos. In the past, the acquisition of such information was of interest only to volcanologists concerned mainly with the internal structures of volcanos.

Although many methods have been developed for the remote subsurface sensing of various geologic structures for a variety of purposes, until very recently none of these have been directed intentionally toward locating molten magma sources.

The major thrust of activities in this area has been close cooperation with other agencies and programs that either are addressing or propose to address this problem with subsurface sensing methods. The Federal agency given primary responsibility for exploration for geothermal sources (presumably including magma) is the U. S. Geological Survey. This program is under the direction of Dr. Patrick Muffler, and close liaison has been maintained with his office.

The USGS plans to conduct its search for a molten magma source on the Island of Hawaii, in the Yellowstone National Park area, in the Geyser area and Long Valley area in Northern California, and in the San Francisco Peaks area near Flagstaff. This agency currently has work under way at some of these locations and plans to have programs going at all of them in the near future.

The Hawaii Institute of Geophysics at the University of Hawaii has a program to perform subsurface sensing surveys of magma sources in the Kilauea Volcano rift zone near Puna, Hawaii. The University of Alaska proposes magma surveys on Augustine Volcano in Cook Inlet, Alaska.

A letter proposal has been sent to Dr. J. Kienle, University of Alaska, outlining the cooperation this Project will extend to him in his proposed Augustine survey. This cooperation will include furnishing personnel and equipment to record seismic traces from a series of explosions proposed by him.

At the Magma Workshop, the working group on the search for the evaluation of magma chambers under the leadership of Dr. Peter Ward, USGS, Menlo Park, California, suggested three levels of exploration: regional reconnaissance, local reconnaissance, and evaluative studies. Regional reconnaissance was envisaged primarily as using existing data on a global, continental, or regional basis to locate areas where magma chambers might exist. Local reconnaissance was viewed as that work done in such areas to decide which should be concentrated on for evaluative studies. It was assumed that at this stage the funds available for work in any one area are small. Evaluative studies then would be done in an area chosen on the basis of the above, and it was assumed that sufficient funds would become available for all types of studies, as the area looked more and more commercially viable.

The recommendations for future work made by this working group were:

"1. The primary need in search and evaluation at the present time is to test the various techniques on known magma bodies so that the effectiveness of the different techniques for finding magma can be determined. Recommended sites include Kilauea Iki, Kilauea's East Rift Zone, and Yellowstone Park where the presence of magma is reasonably certain. Suspected shallow dikes and any plugs in vents of active volcanoes might be good second choices. Active ring dike systems of calderas with recent eruptive histories also appear to be promising localities for such studies. The next step would be to apply the techniques tested in these areas to unknown area.

"2. The next most important need is to determine in more detail the compressional and shear wave velocities, electrical conductivity, and density of typical basaltic and acidic magma in the laboratory as a function of temperatures (from 700° to 1400°C), pressures (of up to a few kilobars), oxygen fugacity, and water content.

"3. A third recommendation is that established geophysical techniques be employed over several old exhumed magma bodies that are eroded to different levels in the structure in order to upward continue the anomalies to the level of the original surface, for comparison with the fields over suspected active magma bodies.

"4. A fourth recommendation is to launch a field effort as soon as is practical to locate an actual magma chamber of plutonic dimensions beneath the conterminous United States."

Based on the above-stated primary recommendation, work has been started on planning for an experiment to evaluate various subsurface sensing techniques over a known molten rock body, Kilauea Iki lava lake. An initial draft of the environmental assessment of such an experiment required by the National Park Service has been proposed. Proposals for contributions to this experiment have been requested from selected University researchers.

Achievements

1. Planned and conducted Magma Workshop to assess problems and recommend research.
2. Completed plans to assist University of Alaska in Augustine volcano seismic survey.
3. Began planning an evaluation experiment of subsurface sensing methods in the known presence of molten rock.

Future Plans

1. Sandia will actively participate with the USGS Menlo Park program of magma exploration. This project will fund the USGS seismic survey of the San Francisco Peaks area in Arizona.
2. Proposals from University researchers to perform a magnetotelluric survey of the same area will be solicited and considered.
3. An experiment to evaluate a variety of subsurface sensing systems in the presence of molten rock at Kilauea Iki lava lake will be commenced.

C. SOURCE TAPPING (J. L. Colp, Principal Investigator)

A problem whose solution is vital to the utilization of magma energy is that of reaching the source and inserting the heat exchanger. As stated earlier, the magma program under consideration at Sandia Laboratories is regarded as one of extremely long range. It is recognized that, in many locations, magma sources will be at depths greater than 10 kilometers below the surface of the earth. It is also realized that conventional drilling technology at this time is limited to depths of about 30, 000 feet, or 10 kilometers. Difficulty has been encountered in past attempts at deep drilling in areas suspected of being near magma sources because of the increasing temperature as the drill neared the possible magma source. This project is not intended to be directly involved in developing deep-drilling methods in the high-temperature magma environment. Other organizations in this country are considering this problem and are initiating programs to solve it. The drilling subcommittee of the U. S. Geodynamics Committee currently recognizes the desirability of developing deep-drilling techniques to reach the magma environment. The Los Alamos Scientific Laboratory has an ongoing program to develop a rock-melting drill that, if successful, might be an ideal means for tapping a magma source.

Although not a part of the magma research effort, Sandia has an ongoing program in drilling research and development. The objective of this program is to devise methods for improving the speed of drilling as well as the depth of drilling. Methods being investigated under this program may be applicable to the magma research project. Close liaison is being maintained with persons working on the drilling research and development program.

As drilling approaches the magma source, it is obvious that temperatures of the rocks above it are going to increase, causing the rocks to approach a plastic state. Two basic questions must be answered: Will a hole through such a hot plastic material stay open and are there methods for keeping it open so that the heat exchanger equipment can be inserted through it into the magma source? Little is known about the physical properties of rocks at these elevated geostatic pressures and temperatures. To answer these questions, Sandia Laboratories is involved in a continuing research program with the Center for Tectonophysics at Texas A&M University to investigate the physical properties of rocks under dynamic stress conditions. This work is being performed under the direction of Dr. John Handin and Dr. Melvin Friedman from that Center.

The objectives of the work at Texas A&M are to determine in static triaxial experiments the mechanical properties and behavior of appropriate igneous rocks under confining pressures of at least 4 kb, temperatures to at least 1000°C, and at strain rates from 10^{-4} sec^{-1} to 10^{-6} sec^{-1}.

Two representative igneous rocks have been chosen for this study: St. Cloud Gray Granodiorite (charcoal granite) and Mt. Hood andesite. The necessary special test equipment has been designed, procured, and is being installed. Preliminary tests at room temperature, dry, 4 kb, 10^{-4} sec^{-1} conditions have been started.

Planning of the Lava Lake Sensing Experiment and discussions with Hawaiian Volcano Observatory personnel have brought out the desirability of easy, continuing access to the molten rock below the crust. At this time, such access requires using a drilling rig. The preliminary design of a magma valve has been started. This device will be attached to the lower end of a stainless steel casing that extends through the crust and into the melt for a few (2 to 3) meters. By actuation of the valve from the surface, experiments can be inserted into and removed from the melt. Samples of melt can be obtained as desired. A patent disclosure has been filed.

Achievements

1. A research contract to study borehole stability under near magmatic conditions has been placed and experiments have begun.
2. Liaison with other programs concerned with deep drilling has continued.
3. Preliminary design of a magma valve has been started. This device is intended for use at the bottom of hole casing extending into molten rock to permit easy access to the melt at any time after installation. This capability for easy access is required in exploratory holes associated with future experiments in lava lakes.

Future Plans

1. Close liaison with other laboratories, agencies, and universities working on deep drilling programs will be maintained.

2. The Texas A&M research contract will be continued with further studies into regimes of higher pressures and temperatures.

3. As part of the Kilauea Iki magma sensing experiment, exploratory holes to delineate the extent of the molten region will be drilled.

4. Development and testing of a magma valve for use in the above-mentioned exploratory holes will be continued.

D. MAGMA CHARACTERIZATION (E. J. Graeber, Principal Investigator)

Discussion

The Magma Workshop held in March included a working group on Chemical and Physical Properties of Magma. From the discussions of that working group came the following assessments and recommendations:

Knowledge of many chemical and physical properties of molten and partly molten rock (magma) and of solid rock at high temperatures is essential for evaluating the feasibility of extracting energy directly from magma bodies. In order to evaluate which properties are most critical, the panel on chemical and physical properties first reviewed the three major stages in developing energy directly from magma: (1) finding a magma body, (2) developing the body (drilling into it and emplacing a heat-transfer device sufficiently strong and corrosion-resistant to last an appreciable period), and (3) extracting energy from the body. Various properties were then reviewed in terms of their bearing on these three stages and in terms of present knowledge about them. Possible approaches toward increasing our knowledge of the critical properties were discussed, and recommendations for future research were prepared.

In brief, the critical factor in evaluating the feasibility of extracting energy from a given magma body appears to be the heat transfer coefficient. Will magma in the body be convecting at a sufficient rate to increase heat extraction significantly over that of a nonconvecting magma? Will convection of appreciable magnitude occur in the presence of an inserted heat exchanger? If not, can convection be induced? The magma very probably will be below liquidus temperatures and will consist of a mixture of melt and crystals with the possible addition of a gas phase. Relevant critical properties that need to be determined are: (1) the distribution of liquid, crystals, gas, and temperature in the magma; (2) the viscosity and density of crystal-liquid gas mixtures; and (3) the heat transfer coefficients over the relevant range of temperature for magmas of different compositions. Other properties that are critical to the exploration and development of magma bodies are: (1) the content of H, C, O, S, F, and Cl in the magma and overlying rock; (2) the strength, elasticity, and ductility of the margin; and (3) in situ physical properties of partially and completely molten magma and hot rock relevant to exploration, such as seismic, electrical, and magnetic properties; density; and permeability.

The panel recommended a two-pronged attack at the problem:

1. The selection of a site overlying a probable magma chamber for exhaustive geologic, geochemical, and geophysical studies, including research drilling to the magma chamber.
2. Measurements in the laboratory of the critical physical properties and related computer modeling; the determination of some properties may require new techniques or instrumentation.

As an outcome of these recommendations, specific rock types have been selected as standards for magma/material compatability tests. The choice for magma simulants was based on (1) a realistic chemistry anticipated to be encountered in the field and (2) rocks that are well characterized with respect to chemical and physical properties. The simulants chosen are Hawaiian Tholeiite (HT), Mount Hood Andesite (MHA) and Newberry Rhyolite Obsidian (NRO). Chemical differences among the three simulants are shown in Table I.

TABLE I

Chemical Analysis of Lava Simulants (weight percent)

	HT	MHA	NRO
SiO_2	49.4	60.7	73.4
TiO_2	2.5	0.9	0.2
Al_2O_3	13.9	17.5	14.2
Fe_2O_3	3.0	3.5	0.2
FeO	8.5	2.7	1.8
MnO	0.2	0.1	0.1
MgO	8.4	3.4	0.2
CaO	10.3	5.5	1.4
Na_2O	2.1	4.2	5.2
K_2O	0.4	1.2	4.1
H_2O^+	0.2	0.2	0.4
H_2O^-	0.1	0.1	0.1
P_2O_5	0.3	0.16	0.02

In order to assess the effects of volatile constituents on metals, the gases shown in Table II have been selected as additives to the simulants for metal compatibility testing. These gases are believed to be representative of exsolved magmatic volatiles, although the quantitative amounts are uncertain. Field tests are under way to corroborate these estimates. Naughton-type gas sampling tubes have been fabricated to sample gases from fumaroles. The sampling apparatus consists of a gas chromatographic column in which acid gases (SO_2, H_2S, etc.) and water vapor are absorbed on activated silica gel; nonabsorbent gases (H_2, CO, etc.) are collected in an attached free volume chamber. For analysis, the free gases are released through an enclosed break-seal to a pressure measuring and gas transfer system. Absorbed gases on the silica gel are desorbed by increasing the column temperature to 300°C. The gas species and amounts are determined by GC/MS.

TABLE II

Dissolved and Exsolved Gas Simulants (weight percent)

Gas	HT	MHA	NRO	Ratio
H_2O	0.5	0.7	0.9	100
SO_2	0.025	0.035	0.045	5
CO_2	0.05	0.07	0.09	10
$HC\ell$	0.005	0.007	0.009	1

Achievements

1. Three magma simulants have been chosen as standards for future magma/material compatibility research.
2. H_2O, SO_2, CO_2, and $HC\ell$ have been selected as likely candidates representative of exsolved magmatic volatiles for future magma/material compatibility research.
3. A number of Naughton-type gas sampling tubes have been fabricated and are available for quick-response field studies as opportunities are presented.

Future Plans

1. Field tests are under way to collect volcanic gases from Mount Baker, Augustine Island, Kilauea vents, and Kilauea Sulphur Banks.
2. Laboratory analysis of the above samples will be made to characterize their content.
3. The selection of magmatic gas simulants will be reevaluated if need be.
4. Laboratory chemical analyses of magma/metal interactions will be continued as the magma/material compatibility research progresses.

E. MAGMA MATERIALS COMPATIBILITIES (M. J. Davis, Principal Investigator)

Discussion

Nickel, iron, and alloys Inconel 718 and 310 stainless steel were immersed in molten rhyolite obsidian (Mono Lake). This magma simulant contains less iron oxides and more silica than the Hawaiian Tholeiite (HT) used in earlier experiments. The rhyolite was not degassed before melting, and the expulsion of dissolved gases produced a foamy structure.

As expected, the nickel and iron showed no visible reaction, while the alloy surfaces acquired a grey oxidized appearance. The degree of reaction of the alloys was considerably less than in the earlier HT tests. The more benign nature of molten rhyolite is attributed in part to the smaller iron oxide content and in part to the foamy structure of the melt. The foam state implies a more viscous melt in which diffusional processes are slowed.

Gas in the bubbles (primarily water vapor) did not produce any detectable effect. The results of these tests are consistent with the criterion postulated on the basis of the HT results; i.e., oxide formation is observed only when the metal phase contains elements whose oxides have a free energy of formation more negative (greater stability) than those of the iron oxides.

During this past year, it was recognized that the more serious threat to long-term compatibility of many metals is posed by the sulfur-containing gases dissolved in magmas. Field tests have been proposed in which selected metals will be immersed in freshly erupted lavas and be exposed to the residual concentration of these magmatic gases. Equipment for these tests has been fabricated. As yet nature has not cooperated, and such tests are still pending.

Gases emitted at volcanic vents are derived in part from the magmatic gases and consist of sulfurous gases and steam admixed with air. Data on the behavior of metals in these gases are needed in material evaluations for surface and near-surface installation and can assist in the interpretation of reactions occurring under subsurface conditions. Samples of various metals have been exposed in the volcanic vents at the Hawaiian Volcanoes National Park. Some samples were also exposed at one of the newly active vents on Mount Baker in the state of Washington.

Preliminary results indicate that pure iron, pure nickel, and ferritic 446 stainless steel are extremely susceptible to attack. The refractory metals molybdenum and tungsten acquired a uniform dark corrosion product layer as did the nickel-base alloy Udimet 700. On the other hand, tantalum and Inconel 718 (nickel-based) appeared inert. The austenitic 310 stainless steel suffered only localized pitting. Additional tests with other stainless steels indicated that none were immune to corrosion by pitting.

As mentioned in the preceding section, the Magma Workshop working group on chemical and physical properties of magma stated that an understanding of the physical and chemical properties of a magma body is critical to the feasibility of economically extracting energy from it. These properties determine the heat transfer coefficient and provide insights into ways of modifying properties such as convection or radiation transport. In addition, a determination of the siesmic and electrical properties will accelerate the successful search for a magma chamber. It is particularly important to determine magma properties over the range of temperatures, pressures, and fugacities that are characteristic of actual magma bodies. Fairly large sample sizes (~100 cc) are required to minimize contamination problems and edge effects. To make these measurements, Sandia is establishing a Materials Characterization Facility designed for high pressures (up to 4 kilobars) and high temperatures (up to 1600°C). High temperatures are possible with a reduction in sample size.

During the past year the equipment needed for this facility has been designed and a major part of it has been contracted for fabrication. The preliminary definition of experiments to be conducted in this facility has been made and they include the following:

A. Viscosity of Multiphase Magma
B. Electrical Properties
C. Thermal Expansion
D. Thermal Conductivity
E. Spectroscopy
F. Density
G. Seismic Properties
H. Strength
I. Ductility
J. Chemical Behavior of Fugitives (H, C, O, S, Cl, F)

<u>Achievements</u>

1. The compatibility of selected material samples with molten rhyolite obsidian has been examined in laboratory tests.
2. Analyses of the above examinations are consistent with the criterion postulated from prior experiments on Hawaiian tholeiite.
3. Various material samples were exposed to actual magmatic gas environments in several volcanic vents on Kilauea.
4. Short-term exposures of material samples were made in recent volcanic vents at Mount Baker in Washington.
5. Inspection and analysis of these samples show that, of the alloys tested, Inconel 718 was most resistant to these environments.
6. The high-temperature/high-pressure Material Characterization Facility has been designed and equipment specified and ordered.
7. Preliminary definition of experiments to be performed in that facility has been made.

Future Plans

1. Laboratory experiments to determine the compatibility of material samples with the selected standard magma simulants (MHA, NRO) will be performed.

2. The laboratory experiments of material compatibility with magma simulants containing certain dissolved gases will be commenced.

3. Analyses of samples exposed to magmatic gas environments will be made to identify the primary corroding agent at work.

4. Additional field tests of material compatibilities in magmatic environments will be performed as opportunity permits.

5. An existing site, specifically designed for hazardous experiments, will be modified for installation of equipment for the Material Characterization Facility.

6. Initial experiments, directed toward developing equipment and procedures to be used in the new facility, will be commenced in the existing low-pressure apparatus.

7. Testing in the new facility is scheduled to start in late spring of 1976.

F. ENERGY EXTRACTION STUDIES (H. C. Hardee, Principal Investigator)

Discussion

A study of possible heat extraction rates (per unit area of heat exchanger surface) from a magma reservoir was completed. Estimates of the heat extraction rates ranged from a low of 1 kW/m^2 to a value of 175 kW/m^2, depending on the assumptions made about the character of the reservoir. The 1-kW/m^2 figure corresponded to the rate expected from a conduction-dominated reservoir and considered a 30-year plant life. The higher figure of 175 kW/m^2 was typical of a magma reservoir with considerable convection. The results of this study were presented in SAND74-0329 (Heat Extraction From a Magma Reservoir). For purposes of comparison, published extraction rates for solar collectors are 0.15 kW/m^2 (daily average) and typical rates for coal-fired boilers are 100 to 200 kW/m^2.

The Molten Lava/Single Tube Boiler Experiment, shown in Figure 3, was run in December. The purposes of this test were the following:

1. To demonstrate that useful amounts of thermal energy could be extracted from a molten lava heat source whose temperature was well in excess of the melt temperature of the heat exchanger.

2. To measure heat extraction rates and the amount of convection in the molten lava and to compare these values with previous calculations.

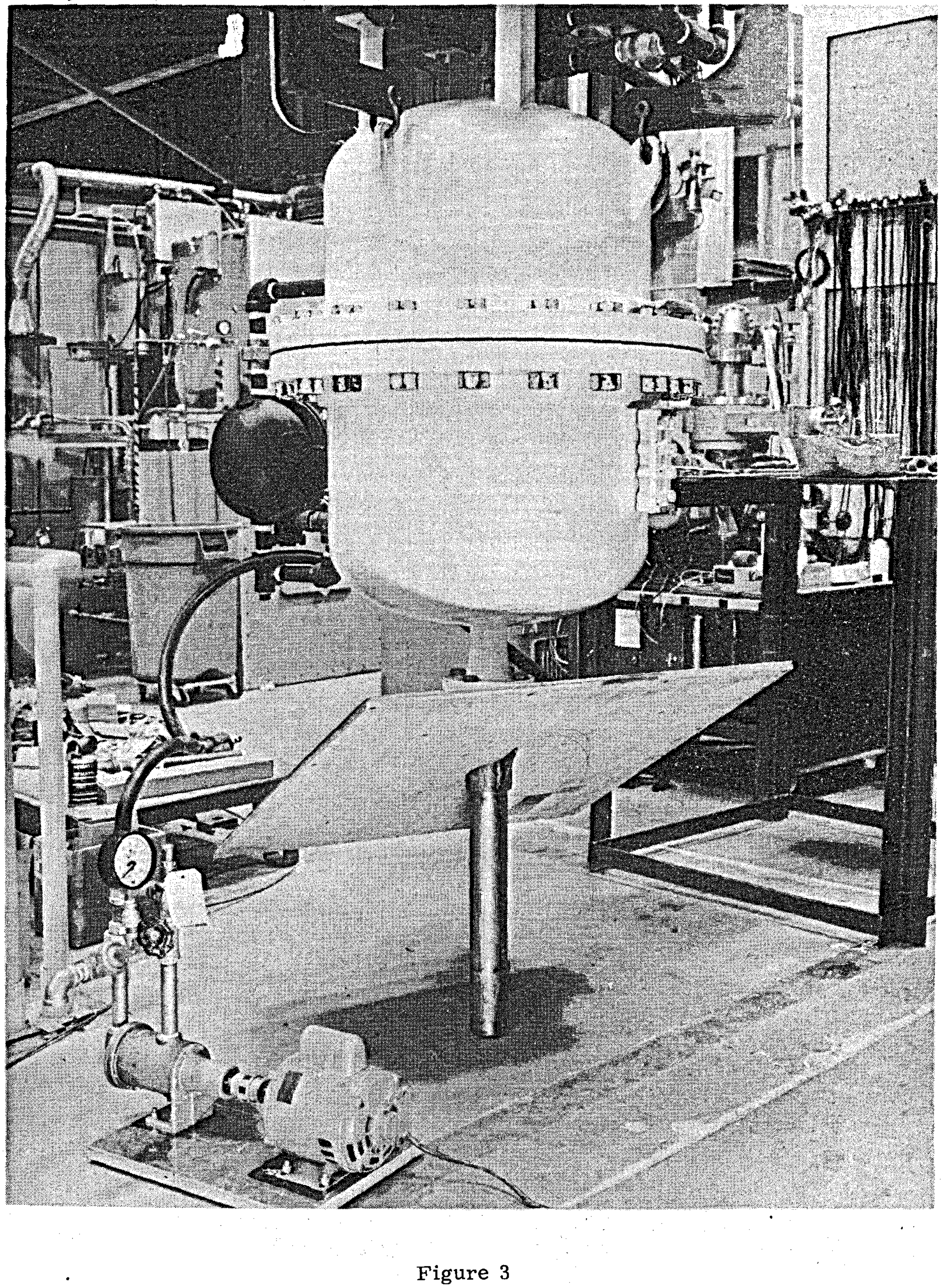

Figure 3

3. To verify calculations for the thermal transient during insertion of the heat exchanger into the molten lava and to show that the resulting stresses and temperatures were not excessive during the transient.

4. To show that corrosion of the heat exchanger in the molten lava was not an insoluble problem.

The test was highly successful. Two runs were made; the first was of 3 hours' duration and the second was of 24 hours' duration. Figure 4 shows the boiler during the test with the heat exchanger element inserted in the molten lava. Corrosion of the heat exchanger was shown not to be a problem, even though the temperature of the molten lava was in excess of the melt temperature of the steel heat exchanger. (Temperature in the molten lava core was measured to be in excess of 1450°C and estimated to be as high as 1650°C.) A solidified lava crust formed next to the heat exchanger as predicted. Energy balance calculations verified that the solidified lava crust next to the heat exchanger surface had a thermal conductivity of 0.005 to 0.006 $\frac{\text{cal}}{\text{cm-s-°C}}$ and that the effective thermal conductivity of the molten lava core was about twice this value. The test data allowed a good check to be made on previous convection calculations for the molten lava core. The surface temperature transient on the heat exchanger was measured and agreed reasonably well with predictions. High-quality steam was produced (i.e., qualities of 99^+ percent). Heat extraction rates of 179 to 314 kW/m^2 were typically measured during the test. The design of this experiment was reported in SAND75-0080 (Design of a Molten-Lava, Single-Tube Boiler Experiment), and the results of the experiment were reported in SAND75-0069 (Molten Lava/Single-Tube Boiler Experiment).

A small turbine/generator unit has been developed and tested for use in future molten lava heat exchanger experiments. The turbine is based on a vane turbine design and can operate on a wide range of saturated steam conditions. The turbine/generator unit is shown in Figure 5. The design description of the turbine was reported in SAND75-0081 (Vane Turbine Development for Molten Lava/Heat Extraction Experiments).

Several heat extraction probes have been designed for use in measuring heat extraction rates from a lava lake. A preliminary test of one of these probes (Mod II) was made in a lava lake in Hawaii. Figure 6 shows the Model I heat extraction probe, and Figure 7 shows the Model II probe.

The early heat extraction calculations neglected the effect of the magma latent heat. In order to examine this effect, a series of numerical CINDA calculations were made to examine the effect of latent heat on heat extraction rates. As a result of certain compensating effects, it was shown that the neglect of latent heat produced a negligible effect on heat extraction rates. With latent heat included, the heat extraction rates were 5 to 10 percent higher than when latent heat was neglected.

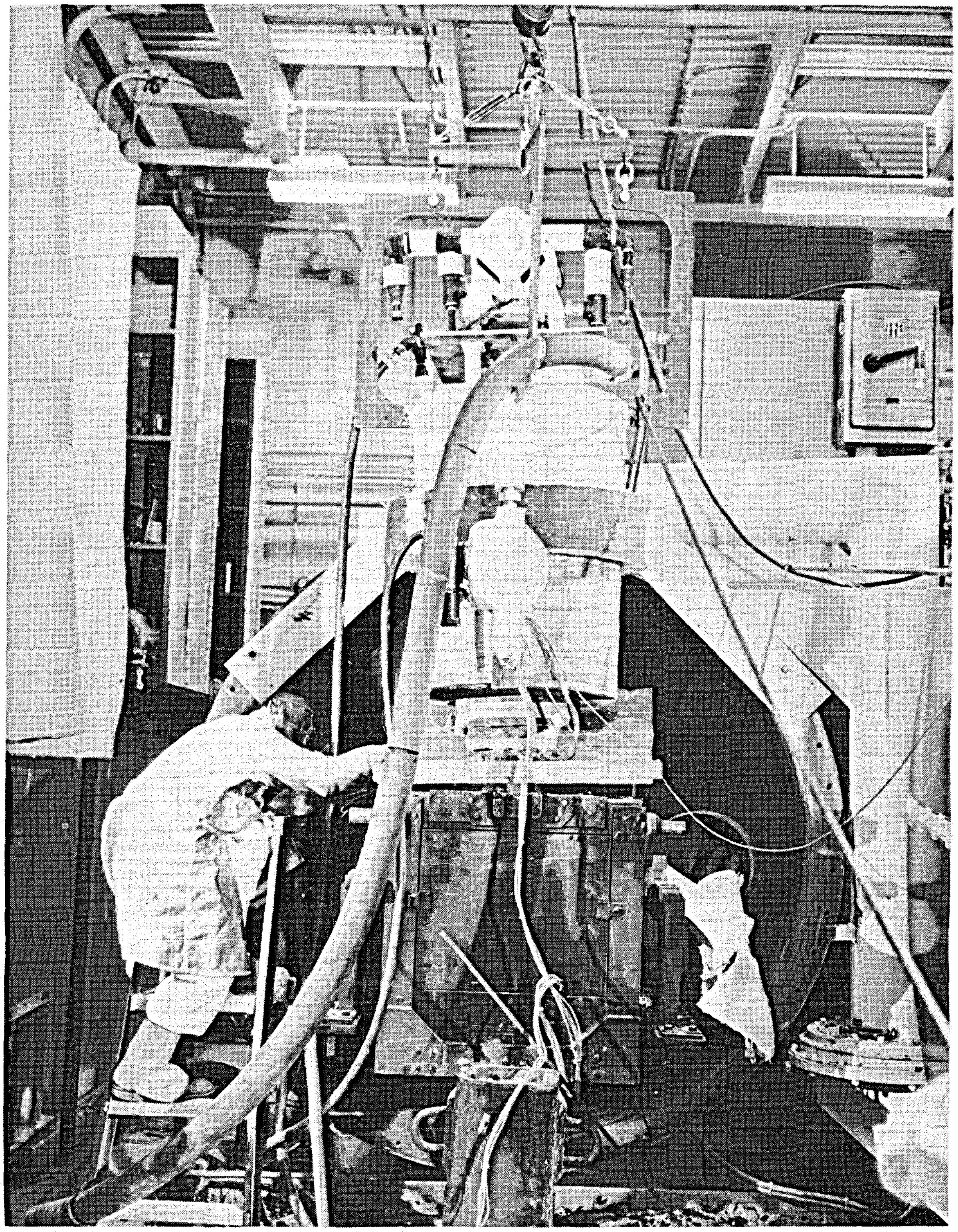

Figure 4

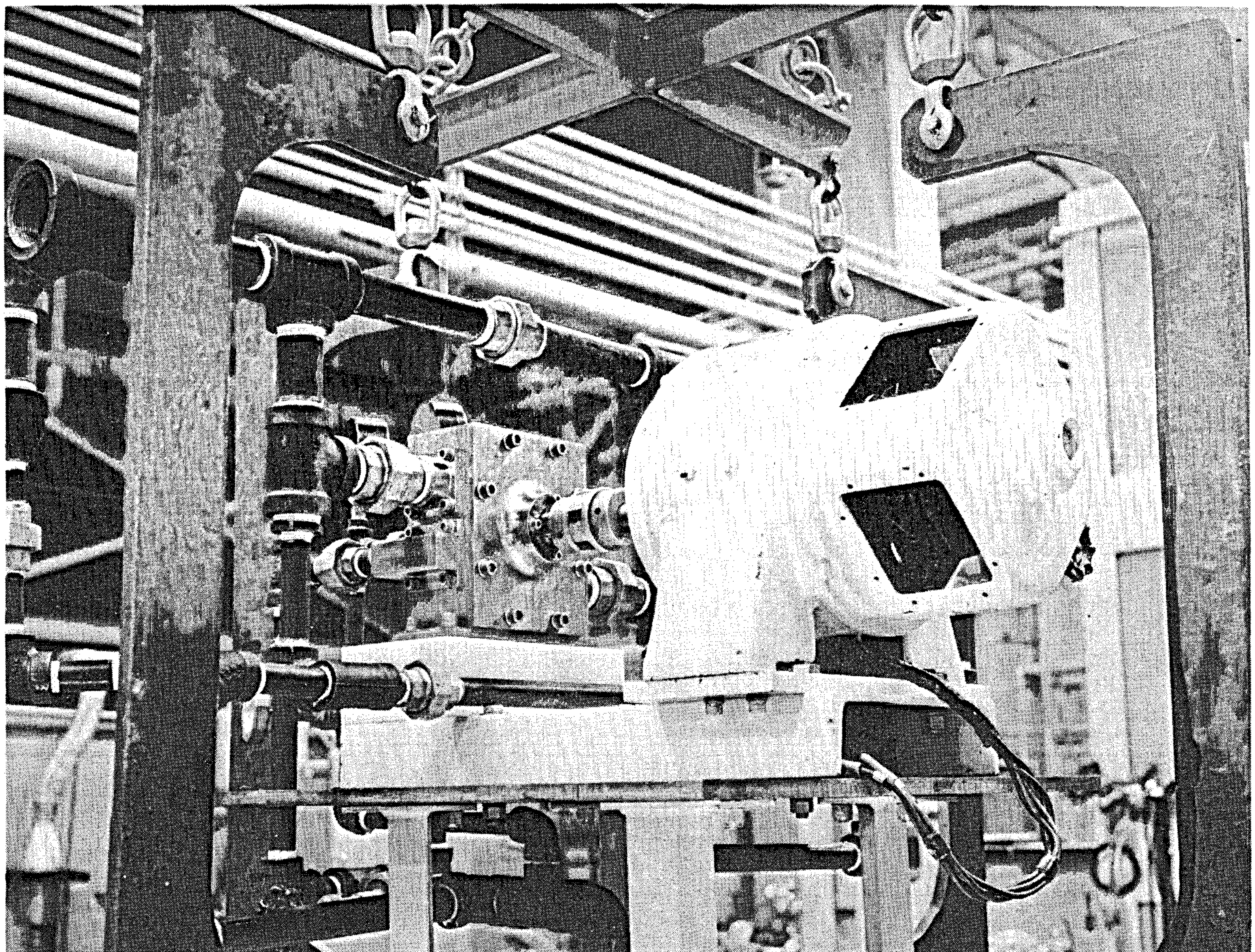

Figure 5

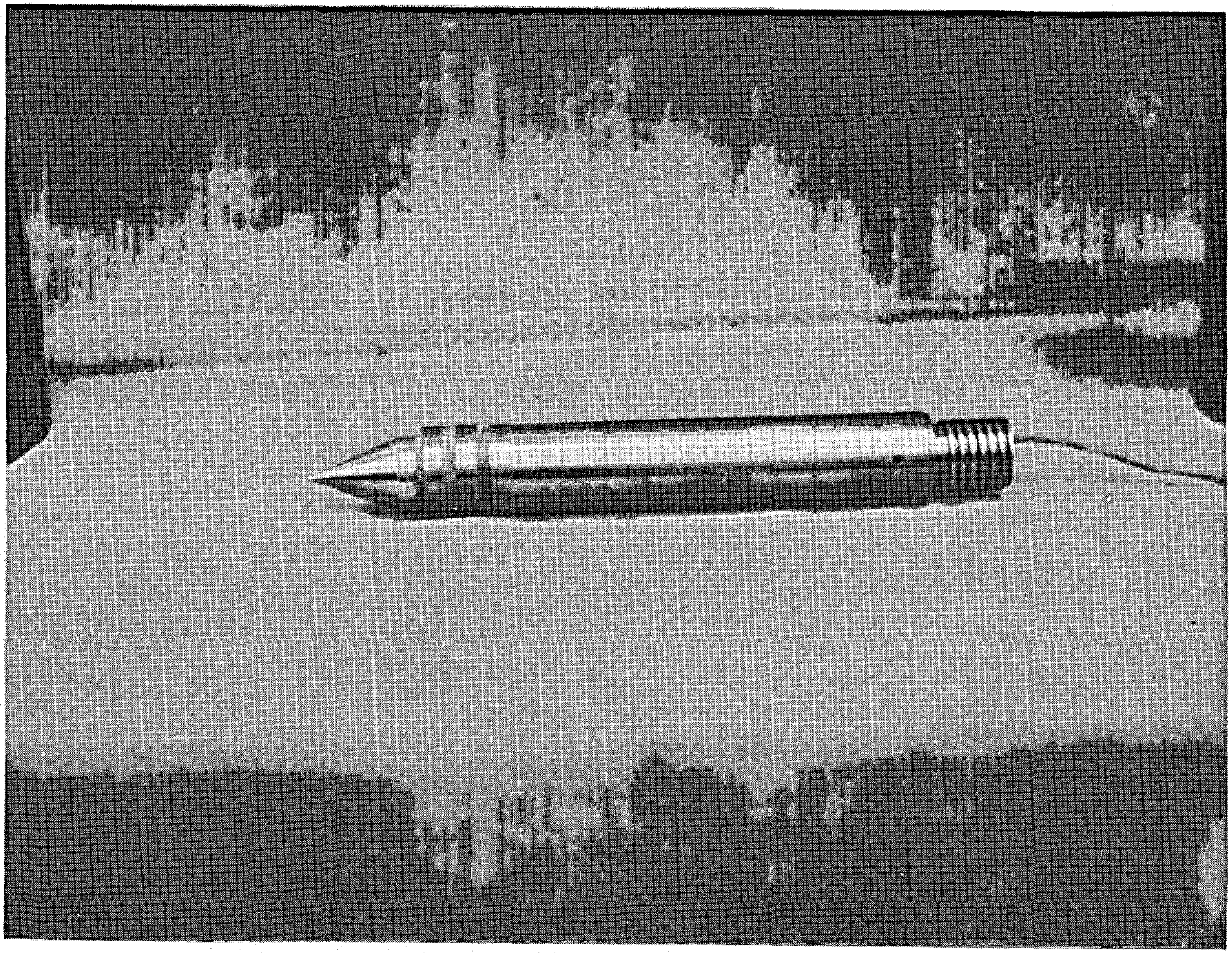

Figure 6

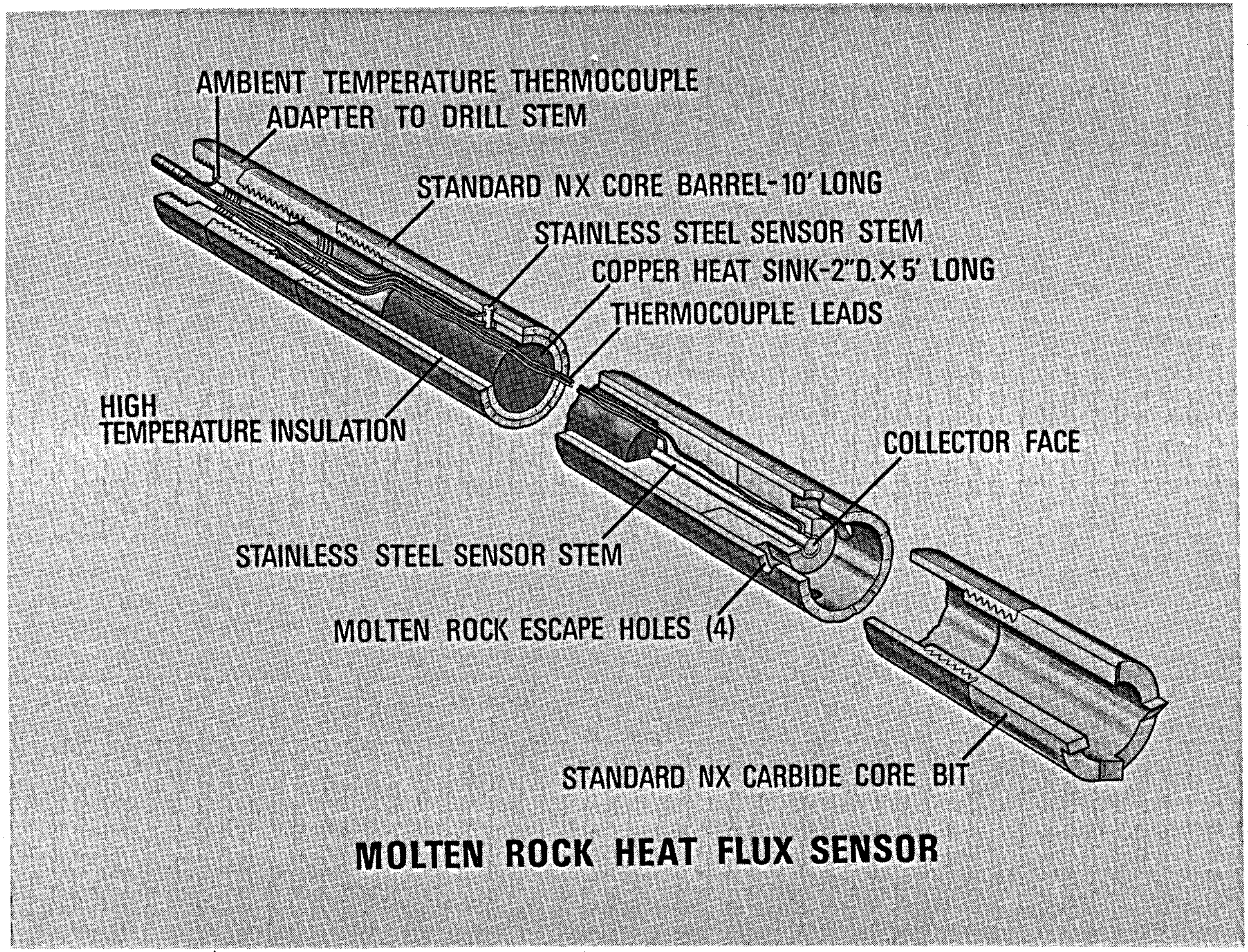
AMBIENT TEMPERATURE THERMOCOUPLE
ADAPTER TO DRILL STEM
STANDARD NX CORE BARREL-10' LONG
STAINLESS STEEL SENSOR STEM
COPPER HEAT SINK-2"D.×5' LONG
THERMOCOUPLE LEADS
HIGH TEMPERATURE INSULATION
COLLECTOR FACE
STAINLESS STEEL SENSOR STEM
MOLTEN ROCK ESCAPE HOLES (4)
STANDARD NX CARBIDE CORE BIT
MOLTEN ROCK HEAT FLUX SENSOR

Figure 7

Some schemes for entering the molten region of a lava lake such as Kilauea Iki involve the solidification of a plug of lava with cooling water after drilling through the solid crust, and the subsequent remelting of the plug by heat from the molten magma. Numerical CINDA calculations were made to determine the time required for remelting of the solidified plug. These calculations indicated that, for older lava lakes with negligible convection, remelting of the solidified plug by conduction effects may be very difficult and, in many cases of interest, impossible.

In preparation for the 20-meter-long tube boiler experiments, planned for FY76, some preliminary model boiling experiments have been run. The model boiling experiments were run with a glass concentric-tube-type boiler using Freon-11 as the fluid in place of water. The experiments allowed the boiling process to be observed visually. Figure 8 shows boiling occurring in the top half of the concentric tube glass heat exchanger.

Preliminary design of Heat Extraction Probe Mod III has been started. Mod III differs primarily from Mod II in its capability to function during the addition of cooling water for the drill bit and in its capacity for transmitting data continuously during drilling.

Achievements

1. Completed molten lava/single-tube boiler experiment
2. Confirmed heat extraction calculations in ML/STB experiment
3. Obtained rough check on thermal conductivity value for molten lava
4. Verified calculations for thermal transient during insertion of single-tube boiler into molten lava
5. Completed development work on small turbine/generator for use with future heat extraction experiments
6. Designed and tested heat extraction probe for use in a lava lake
7. Initiated design of a 20-meter-long tube boiler experiment
8. Performed numerical heat extraction calculations for a magma reservoir and examined effect of latent heat on the heat extraction rates
9. Performed numerical calculations for the remelt of a solidified lava plug in a lava lake (this problem related to insertion of test probes in a lava lake.)

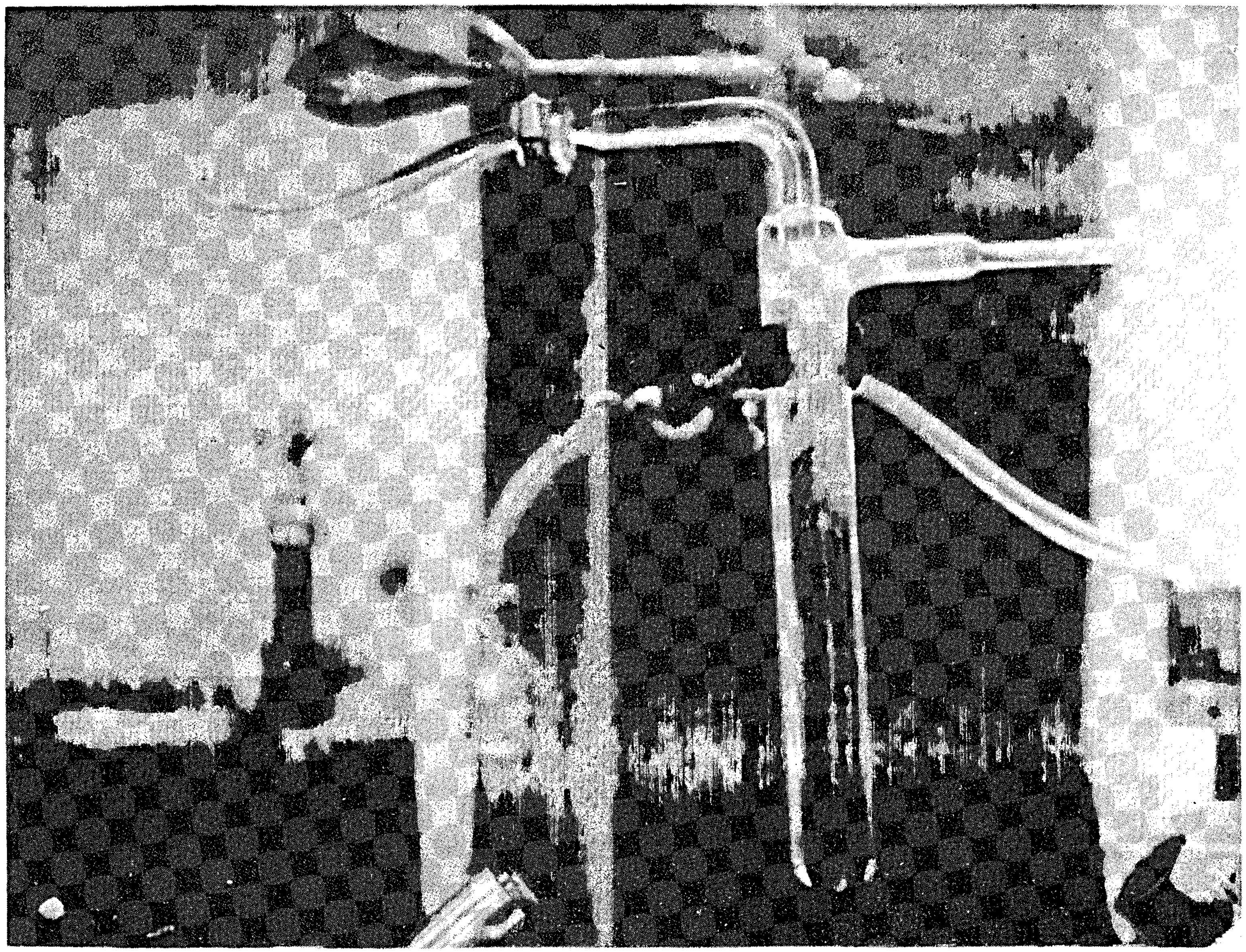

Figure 8

Future Plans

1. 20-Meter-Long Tube Boiler Experiment

   a. Instrument the long-tube boiler so that film boiling and flow instabilities can be detected.

   b. Vary the significant boiler-tube operating parameters such as surface heat rate, flow rate, and system pressure so that the film boiling and flow instability regimes can be characterized.

   c. Vary boiler design so that film boiling and flow instability regimes can be characterized for each design.

   d. Extend present knowledge of forced convection gas-liquid two-phase heat transfer to include the effects of varying hydrostatic head.

   e. Mathematically model the long-tube boiler and correlate the experimental data so that the results can be extended to long-tube downhole heat exchangers.

   f. Choose the best design for the long-tube heat extractor for the lava lakes experiment.

   g. Determine the best methods for instrumenting the long-tube heat extractor for the lava lakes experiment.

   h. Maintain the test facility so that future designs of long-tube downhole heat exchangers can be tested.

   i. Investigate the transient start-up problem.

   j. Report on the various phases of the problem.

2. Heat Extracting Probe Mod III

   a. Build and test one of the commutator connectors.

   b. Test to determine if the Mod III Probe design will function during the addition of cooling water.

   c. Determine, by testing, the cooling effect on the copper heat sink of the addition of drill cooling water.

3. Extend calculations to investigate the transient solidification of a plug in a lava lake associated with the addition of cooling water and the possible remelting of this region.

   a. Determine the effect of L/D.

   b. Determine the conduction limit (no remelt).

   c. Determine the remelt threshold.

   d. Report with calculations.

GENERAL ACTIVITIES

A. Publications

Colp, John L., Magma Tap - The Ultimate Geothermal Energy Program, SAND74-0253, Sandia Laboratories, Albuquerque, NM, November 1974.

Hardee, H. C., Heat Extraction from a Magma Reservoir, SAND74-0329, Sandia Laboratories, Albuquerque, NM, December 1974.

Hardee, H. C. and M. E. Fewell, Molten Lava/Single-Tube Boiler Experiment, SAND75-0069, Sandia Laboratories, Albuquerque, NM, February 1975.

Fewell, M. E. and P. C. Montoya, Vane Turbine Development for Molten Lava/Heat Extraction Experiments, SAND75-0081, Sandia Laboratories, Albuquerque, NM, June 1975.

Fewell, M. E., H. C. Hardee and P. C. Montoya, Design of a Molten Lava/Single-Tube Boiler Experiment, SAND75-0080, Sandia Laboratories, Albuquerque, NM, July 1975.

Stephens, H., A Penetrometer Mounted Radiometer for Rapid In Situ Measurement of Magma Temperature, SAND74-0413, Sandia Laboratories, Albuquerque, NM, January 1975.

Davis, M. J. and D. J. Mottern, Material Selection and Processing for the Molten Lava/Single-Tube Boiler Experiment, SAND75-0055, Sandia Laboratories, Albuquerque, NM, June 1975.

Haaland, David M., Magma Fuel Cell, SAND75-0074, Sandia Laboratories, Albuquerque, NM, February 1975.

Colp, John L., Magma Tap - The Ultimate Geothermal Energy Program (Abstract), SAND74-5311A, Program and Abstracts of Papers, Circum-Pacific Energy and Mineral Resources Conference, Honolulu, HI, August 1974.

Colp, John L. and G. E. Brandvold, Direct Magma Tap - A Geothermal Energy Dream? (Abstract), SAND74-5016A, Abstracts with Programs, Geological Society of America, V. 6, No. 7, Annual Meeting, Miami Beach, FL, November 1974.

Colp, John L. and G. E. Brandvold, Sandia Magma Energy Project (Abstract), SAND75-5492, Abstracts, Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, CA, May 1975.

B. Presentations

Colp, John L., Magma Tap - The Ultimate Geothermal Energy Program, Circum-Pacific Energy and Mineral Resources Conference, Honolulu, HI, August 1974.

Colp, John L., Can the Dream of Using Magma Energy Come True?, Albuquerque Geological Society Meeting, Albuquerque, NM, October 1974.

Colp, John L. and G. E. Brandvold, Direct Magma Tap - A Geothermal Energy Dream? Geological Society of America Annual Meeting, Miami Beach, FL, November 1974.

Colp, John L., M. J. Davis, E. J. Graeber and H. Hardee, Sandia Magma Energy Project, Geoscience Seminar, University of Hawaii at Manoa, March 1975.

Colp, John L., Magma Energy Research at Sandia, American Association for Advancement of Science, Southwestern and Rocky Mountain Division Meeting, Los Alamos, NM, April 1975.

C. Conferences Attended

Circum-Pacific Energy and Mineral Resources Conference, Attendees: J. L. Colp, E. J. Graeber.

National Science Foundation Geothermal Conference, NASA Jet Propulsion Lab, Attendee: J. L. Colp.

Geological Society of America Annual Meeting, Attendee: J. L. Colp.

American Geophysical Union Annual Meeting, Attendee: J. L. Colp.

Sandia/USGS Magma Workshop, Attendees: J. L. Colp, M. J. Davis, E. J. Graeber, H. C. Hardee.

Second United Nations Symposium on the Development and Use of Geothermal Resources, Attendees: G. E. Brandvold, J. L. Colp.

D. Meetings and Consultations

Los Alamos Scientific Laboratory - T. McGetchin: J. L. Colp.

Sandia Laboratories - Prof. J. J. Naughton, University of Hawaii: M. J. Davis, E. J. Graeber, J. L. Colp, R. Sallach.

University of Texas, Dallas - Prof. J. Combs: J. L. Colp.

Southern Methodist University - Prof. D. Blackwell: J. L. Colp.

University of Texas, Austin - Prof. F. Bostick: J. L. Colp, C. L. Schuster.

Texas A&M University - Prof. J. Handin and M. Friedman: J. L. Colp.

Sandia Laboratories - D. Peck, R. Decker, J. Hermance, P. Ward: M. Davis, E. Graeber, H. Hardee, J. L. Colp.

Sandia Laboratories - T. McGetchin, J. Echelberger, R. Gooley (all LASL): M. Davis, E. Graeber, J. L. Colp.

Sandia Laboratories - A. Basulis, R. Atkins, Hughes Aircraft Company: G. E. Brandvold, H. Hardee, J. L. Colp.

Southern Methodist University - Prof. D. Blackwell: E. W. Reece, J. L. Colp.

Stanford University - Profs. R. Anderson and W. Luth: H. Hardee, J. L. Colp.

Sandia Laboratories - G. Kolstad and Sandia Magma Energy Advisory Panel: G. E. Brandvold, M. Davis, H. Hardee, E. Graeber, J. L. Colp.

Sandia Laboratories - Prof. G. Bodvarsson, Oregon State University: G. E. Brandvold, J. L. Colp, E. J. Graeber, H. C. Hardee.

Sandia Laboratories - Dr. M. Krupka, LASL: E. J. Graeber, R. Sallach.

Sandia Laboratories - Dr. Erico Barbier, Italian National Research Council: G. E. Brandvold, E. J. Graeber.

Hawaiian Volcano Observatory - Drs. D. Peterson, R. Tilling, J. Lockwood, C. Zablocki: J. L. Colp, M. Davis, E. J. Graeber, H. C. Hardee.

University of Hawaii, Hilo - Prof. B. Findlayson: M. Davis, E. J. Graeber.

University of Hawaii, Manoa - Profs. J. Shupe, P. Yuen, M. Htun, J. Larsen-Basse: M. Davis, E. J. Graeber.

ERDA Honolulu Office - Bill Hills, ERDA: J. Colp.

USGS National Center - Dr. D. Peck: J. L. Colp.

ERDA Headquarters - Dr. George Kolstad: J. L. Colp.

Stanford University - Prof. W. Brigham: J. L. Colp.

USGS Menlo Park - Dr. P. Ward: J. L. Colp, Prof. J. Hermance.

Texas A&M University - Prof. M. Friedman: J. L. Colp.

E. Requests for Information

John Michaels, Dresser Industries, Los Angeles, CA.

C. Marchetti, International Institute for Applied Systems Analysis, Laxenburg, Austria.

G. Kelsey, AWARE Magazine, Madison, WI.

G. J. Taylor, Florida State University, Melrose, FL.

Dr. C. W. Burnham, Pennsylvania State University, University Park, PA.

J. W. Patterson Iowa State University, Ames, IA.

M. J. Lippman, University of California, Berkeley, CA.

N. Perona, ERDA Headquarters, Washington, D. C.

L. Hodges, Ames Laboratory, Ames, IA.

DISTRIBUTION:

University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, CA 94550
Attn: R. Austin, Project Leader - Geothermal Program

Division of Geothermal Energy (4)
US ERDA
Washington, DC 20545
Attn: L. Ball
J. C. Bresee
J. Walker
L. B. Werner

Office of Nuclear & Energy Technology Affairs
Department of State
Washington, DC 20520
Attn: J. L. Bloom

University of Texas
Engineering - Science Bldg. 623
Austin, TX 78712
Attn: Prof. F. X. Bostick

Petroleum Engineering Department
Stanford University
Stanford, CA 94305
Attn: Prof. W. E. Brigham

Department of Earth Sciences
Dartmouth College
Hanover, NH 03755
Attn: Prof. R. W. Decker, Chairman

University of Texas
Center for Energy Studies
Austin, TX 78712
Attn: Dr. M. Dorfman

U. S. Geological Survey (2)
Federal Center
P. O. Box 25046
Denver, CO 80225
Attn: Dr. G. Eaton
Dr. F. Frischknecht, MS 964

Texas A&M University (2)
Center for Tectonophysics
College Station, TX 77843
Attn: Prof. M. Friedman
Dr. R. E. Wainerdi

University of Hawaii at Manoa
Hawaiian Institute of Geophysics
Honolulu, HI 96822
Attn: Dr. A. S. Furumoto

US ERDA
Idaho Operations Office
550 2nd Street
Idaho Falls, ID 83401
Attn: J. Griffith
Idaho Geothermal Program Mgr.

Aerojet Nuclear Company
550 2nd Street
Idaho Falls, ID 83401
Attn: J. F. Kunze, Mgr. Geothermal Projects

Director
Hawaii Volcanoes National Park
Hawaii 96718

Lamont-Doherty Geological Observatory
Palisades, NY 10964
Attn: Dr. J. F. Hermance

University of Alaska
Geophysical Institute
Fairbanks, AK 99701
Attn: Dr. J. Kienle

Los Alamos Scientific Laboratory (5)
P. O. Box 1663
Los Alamos, NM 87544
Attn: C. Herrick, CMB-8
T. McGetchin, Q-21
J. C. Rowley, Q-23
M. C. Smith, Group Leader, Q-22
R. F. Taschek, Assoc. Director for Research

US ERDA (10)
Division of Physical Research
Washington, DC 20545
Attn: G. A. Kolstad

Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN 37830
Attn: W. L. Marshall

University of California (2)
Lawrence Berkeley Laboratory
Berkeley, CA 94720
Attn: K. Mirk, Project Engineer
P. A. Witherspoon

U. S. Geological Survey (3)
Field Geochemistry & Petrology
345 Middlefield Road
Menlo Park, CA 94025
Attn: Dr. J. G. Moore
L. J. P. Muffler, Geothermal Program
Dr. P. Ward

DISTRIBUTION (Cont):

US ERDA
Albuquerque Operations Office
P. O. Box 5400
Albuquerque, NM 87115
Attn: D. K. Nowlin, Director
Special Programs Division

Bill Ogle
3801 B West 44th Avenue
Anchorage, AK 99503

Dr. Dallas Peck
U. S. Geological Survey
Reston, VA 22092

Dean John Shupe
College of Engineering
University of Hawaii at Manoa
Honolulu, HI 96822

Ohio State University
Department of Metallurgical Engineering
Corrosion Center
116 W. 119th Street
Columbus, OH 43210
Attn: Prof. R. Staehle

Battelle Memorial Institute
Pacific Northwest Laboratory
P. O. Box 999
Richland, WA 99352
Attn: D. Stewart, Manager
Geothermal Program

U. S. Geological Survey
Hawaii Volcano Observatory
Hawaii National Park, HI 96718
Attn: R. Tilling, Chief Scientist

Prof. G. Bödvarsson
Oregon State University
Corvallis, Oregon 97331

1200 W. A. Gardner
1280 T. B. Lane
1283 H. C. Hardee
1300 D. B. Shuster
5000 A. Narath
5100 J. K. Galt
5700 J. H. Scott
5710 G. E. Brandvold
5715 R. H. Braasch
5715 J. L. Colp (20)
5718 M. M. Newsom
5730 H. M. Stoller
5733 C. L. Schuster
5800 R. S. Claassen
5820 R. L. Schwoebel
5822 R. E. Whan
5822 E. J. Graeber
5830 M. J. Davis
5831 N. J. Magnani
5831 P. J. Modreski
5831 T. Gerlach
6010 T. F. Marker
8266 E. A. Aas (2)
3141 C. A. Pepmueller (Actg) (5)
3151 W. L. Garner (3)
For ERDA/TIC (Unlimited Release)
ERDA/TIC (25)
(R. P. Campbell, 3171-1)